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Impact of zero energy buildings on medium-to-long term building energy consumption in China

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ABSTRACT

The future development pathway of upgrading building energy codes in China remains unclear. No studies have addressed the impacts of Zero Energy Building (ZEB) on medium-to-long term building energy consumption. By reviewing the development and enforcement of building energy codes in China in the last 30 years (1986–2016), together with the analysis of energy consumption of ultra-low energy building and nearly-zero energy building (nearly-ZEB) demonstration projects (2012–2017), this study proposes a three-definition hierarchy of ultra-low energy buildings, nearly-ZEB and ZEB as the successive building energy codes upgrading goals towards 2050. Six scenarios, BAU to leapfrog scenarios, are developed to study the building energy consumption from 2025 to 2050. The results show that the peak of the building energy consumption decreases and the occurrence time advances. In general, only if the ultra-low energy building, nearly-ZEB and ZEB account for more than 50% of total floor area does the building energy consumption begin to decrease. In moderate development scenario, which is most likely to occur, the peak will appear in 2035 with the amount of 567 million tce. Compared to BAU scenario, in leapfrog scenario, the accumulated saving of fossil fuels can be reduced by up to 9380 million tce till 2050, which contributes most to mitigation of climate change.

1. Introduction

As the world's second-largest economy, China has set an energy consumption cap to improve industrial efficiency and control greenhouse gas emissions. China is also pushing supply-side structural reforms to decouple economic growth from energy consumption. In 2015, China submitted its Intended Nationally Determined Contribution to the United Nations Framework Convention on Climate Change, pledging to peak CO_2 emissions by 2030 and strive to achieve it as soon as possible. The *Energy Supply and Consumption Revolution Strategy (2016–2030)* published in 2017 also sets ambitious targets, including controlling China's primary energy consumption within 6 billion tce by 2030, with non-fossil fuels higher than 20%. The building sector presents a great challenge to achieving such goals, as it significantly affects the environment and energy use. Globally, public and residential buildings account for 20.1% of the total delivered energy consumed (EIA, 2017). In China, the building sector consumed approximately 20% of the primary energy and approximately 23% of the electricity consumed in 2015 (THUBERC, 2017).

Future building energy efficiency pathways involve rapid and extensive transitions. Many developed countries have proposed goals and policies for zero energy buildings (ZEBs) (Panagiotidou and Fuller, 2013). The goals of ZEBs generally include 1) reducing energy demand to an extreme low level via passive techniques; 2) improving the energy efficiency of products; and 3) replacing the remaining fossil fuels by various sources of renewable energy (Lund, 2007). There is no doubt that the development of ZEBs will restructure the energy mix in the building sector.

1.1. United States

The Building Technology Program of the US Department of Energy has set the goal to achieve marketable net zero energy homes by 2020 and public net zero energy buildings at low incremental cost by 2025. The state of California has also proposed bold strategies for designing and constructing all new residential and public buildings as net zero energy buildings as of 2020 and 2030, respectively. The US Department of Energy recently released a common ZEB definition that specifies measurement methods and design strategies development (DOE, 2015). Meanwhile, the new building energy codes released in 2016 provide in excess of 30% energy savings compared to the codes from a decade ago (DOE, 2016).

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Abbreviations

A	Building area
e	Energy intensity
E	Total building energy use
f	Area percentage of different building types
i	Climate zones
k	Types of building, residential and public buildings
C	Cold climate zone
CABR-NZEB	Nearly-ZEB China Academy of Building Research
HSCW	Hot summer and cold winter climate zone
HSWW	Hot summer and warm winter climate zone
MoC	Ministry of Construction of China
MoHURD	Ministry of Housing and Urban-Rural Development of China
Nearly-ZEB	Nearly zero energy buildings
SC	Severe cold climate zone
ZEB	Zero energy buildings

1.2. European Union

The 2002 Energy Performance of Buildings Directive (EPBD) and its 2010 recast specify measures for reducing energy consumption in the building sector. It states that member states shall ensure that new buildings occupied and owned by public authorities are nearly-ZEBs by 31 December 2018 and that all new buildings are nearly-ZEBs by 31 December 2020. Due to the difference in climates and local conditions, the EPBD asks all member states to develop their own nearly-ZEB definition and integrated methodology for measuring energy performance (D'Agostino, 2015; ECOFYS, 2014).

1.3. Asia

In 2014, the Japanese cabinet approved an energy policy requiring all newly constructed public buildings to be zero energy by 2020 and all newly built houses to be zero energy by 2030. In 2009, the South Korean government announced the Activation Plan for Green Building. According to this plan, all newly constructed buildings should be ZEBs by 2025. Subsequently, in 2014, The Activation Plan of Zero Energy Building Corresponding to Climate Change was issued, accomplishing top-level ZEB design (Liu et al., 2006).

In China, many researchers have explored the role of building energy efficiency in addressing climate change mitigation (Li, 2008). Recently, studies have focused on the possible contributions of buildings to China's sustainable energy system in the medium-to-long term, from aspects of renewable energy in buildings (Zhang et al., 2015) and heating strategies (Xiong et al., 2015) to total building energy consumption (Jiang et al., 2014; McNeil et al., 2016; Peng and Jiang, 2015; Tan et al., 2018; Zhang and Gu, 2017). Jiang et al. (2014) used the integrated IPAC-LEAP model to study the low carbon building scenario in China and its policy roadmap. Their results suggest that building energy demand will peak in 2040, at the amount of nearly 800 million tce. Peng and Jiang (2015) estimated that the building energy consumption should be controlled under 1100 million tce by considering the effects of population, the urbanisation ratio and the total building amount. Zhang and Gu (2017) indicated that building energy consumption will peak in 2031 at 1370 million tce. Recently, Tan et al. (2018) showed that although the terminal energy consumption of the building sector maintains a low growth rate under the synergistic emission reduction scenario, no energy demand peak will occur in China until 2050.

Although many studies have estimated the energy saving potentials of implementing various policies and strategies, no consensus on the energy consumption peak of the building sector in China has been reached. ZEBs use much less energy than traditional buildings. Based on the history and status of building energy efficiency and international consensus, ZEBs represent China's ultimate goal. Therefore, ZEB development is expected to significantly influence the energy consumption of the building sector. However, no studies have analysed the impacts and challenges of ZEBs for medium-to-long term building energy consumption. It remains unclear whether and when a peak demand will occur in the building sector by developing ZEBs. Furthermore, the many technical barriers to ZEB development make the development pathway of building energy efficiency towards ZEBs in the next few decades unclear.

In this study, a definition hierarchy towards ZEBs is established based on history, China's national conditions and the international consensus about the next 30 years. On the basis of existing demonstration projects, this study also analyses the technical strategies regarding ZEB development in China. It then proposes six possible development scenarios to explore the peak building energy consumption and energy saving potentials by considering the impact of ZEBs in China.

2. History and status of building energy efficiency in China

2.1. Three-step upgrading plan for building energy efficiency codes (1986–2016)

The climate in China is extremely diverse. Taking temperature and humidity as primary indicators, precipitation, heating and cooling degree days as secondary indicators, the Chinese national regulation *Thermal Design Code for Civil Building GB50176* defines five climate zones in China. They are severe cold (SC), cold (C), hot summer and cold winter (HSCW), hot summer and warm winter (HSWW), and temperate (T) zones (Lang, 2004).

In China, energy efficiency efforts started in the early 1980s. During that time, more than half of the total building area of China was located in severe cold and cold regions. Furthermore, the length of the heating season ranged from three to six months. Therefore, the energy consumption for heating constituted the main part of the total building energy consumption (Lang, 2004). In 1982, with support from the Ministry of Construction (MoC), the first study related to building energy efficiency in China, 'Study on energy conservation of heating for residential buildings in North China', was launched. As a result, in August 1986, the MoC officially issued the standard *Energy Conservation Design Standard for New Heating in Residential Buildings JGJ 26–86*. Through a thorough study monitoring building energy consumption and building components, the goal of the standard was a 30% decrease in heating energy consumption compared to the baseline buildings built in the early 1980s. The revised version (JGJ26-95) aimed to achieve a further reduction of 30% from the 1986 baseline levels. Finally, JGJ26 debuted in 2010, targeting an energy reduction of 30% on the basis of JGJ26-95, representing a 65% reduction from the baseline buildings built in the 1980s.

Similarly, for public buildings, the MoC, lately known as Ministry of Housing and Urban-Rural Development of China (MoHURD), officially issued the first energy efficiency standard (GB50189-2005) in 2005. GB50189-2005 aimed to decrease building energy consumption by 50% compared to the baseline buildings built in the 1980s. In 2014, GB50189-2014 was issued with the goal of further reducing building energy consumption by 30% based on GB50189-2005.

After three decades of development, China has accomplished its three-step '30%-50%-65%' plan for building energy efficiency proposed in the early 1980s (Fig. 1).

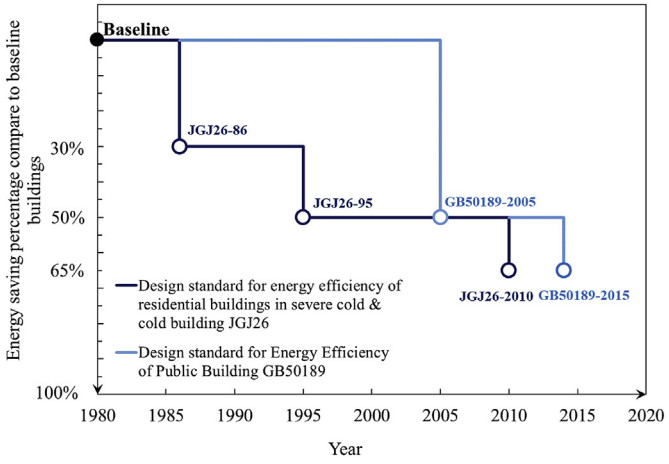


Fig. 1. Building energy efficiency codes upgrading roadmap in China (1986–2016).

2.2. Development of ZEB

2.2.1. Preliminary exploration of ZEBs (2009–2014)

Established in 2009, the US-China Clean Energy Research Center Building Energy Efficiency Consortium aims to promote nearly-ZEBs and ZEBs. Through pilot studies from 2011 to 2014, scientists and researchers from both China and the United States jointly designed and built the first demonstration of a nearly-ZEB in China, specifically the nearly-ZEB China Academy of Building Research (CABR-NZEB). Adhering to the principle of 'passive building, proactive optimisation, economic and pragmatic', ambitious annual energy consumption goals were set for the CABR-NZEB during the design stage: provide heating in winter with zero fossil fuel use, reduce summer cooling energy by 50%, reduce lighting energy by 75% and reduce total energy consumption by more than 80% from the average level.

In 2012, with the support of MoHURD and the German Federal Ministry of Transport, Building and Urban Development, the Center of Science and Technology of MoHURD and the German Energy Agency introduced advanced international concepts and technologies to China and a series of ultra-low energy demonstration projects, such as the 'Water Front' in Hebei Province and the 'Chenergy Green Passive Apartment' in Heilongjiang Province, were built. Hu (2014) pointed out that the 'Water Front' project may reduce heating and cooling demand 74% and 21%, respectively.

2.2.2. Guidelines and standards (2014–2018)

In China, guidelines are developed to standardize the design and consulting methods according to the best practices, which aims to set national standards. National standards are then designed for technical requirements consistent across China.

Based on international cooperation achievements and actual domestic conditions, MoHURD authorised the China Academy of Building Research to compile *Technical Guidelines for Passive Ultra-Low Energy Green Building* and the national standard *Technical Standard for Nearly-Zero Energy Building* in China. The guideline was officially issued in November 2015. The national standard plan to be released in 2019.

The technical guideline is more emphasis on the passive strategies, while the national standard extends the scope to design, construction, testing and so on. Also, the national standard defines ultra-low energy buildings, nearly-ZEB and ZEB in China. Meanwhile, the technical guideline only focusses on residential buildings, while the national standard takes account of public buildings as well. Both the technical

Table 1
Incentive policies to promote nearly-ZEB in China.

Provinces/Cities	Release Time	Key terms[a]
Shandong Province	2017.01	1. Subsidies
Beijing	2017.06	1. 300,000 m^2 by 2020 2. Subsidies: ● Before 2017-10-08, 1000CNY/m^2, no more than 30 million CNY for each project ● 2017-10-09 to 2018-10-08, 800CNY/m^2, no more than 25 million CNY for each project ● 2018-10-09 to 2019-10-08 600CNY/m^2, no more than 20 million CNY for each project
Hebei province, Shijiazhuang	2018.02	1. 1 million m^2 by 2020 2. Land use support 3. Floor area ratio bonus 4. Allow real estate price rise 30% 5. Reduced city infrastructure supporting fees 6. Subsidies ● 2018–2019, 200CNY/m^2, no more than 3 million CNY for each project ● 2020, 100CNY/m^2, no more than 2 million CNY for each project
Hebei province, Hengshui	2018.05	1. 50,000 m^2 by 2020
Hebei province, Baoding	2018.06	1. Land use support 2. 20% newly built buildings are nearly-ZEB by 2020 3. Allow real estate price rise 30% 4. Subsidies ● 100CNY/m^2, no more than 3 million CNY for each project
Hebei province, Zhangjiakou	2018.07	1. Building area bonus 2. Subsidies ● 100CNY/m^2, no more than 3 million CNY for each project
Tianjin	2018.09	1. 300,000 m^2 by 2020 2. Subsidies ● 300CNY/m^2, no more than 3 million CNY for each project 3. Building area bonus
Henan province, Zhengzhou	2018.09	1. 600,000 m^2 by 2020 2. Subsidies ● 2018, 500CNY/m^2, no more than 15 million CNY for each project ● 2019, 400CNY/m^2, no more than 12 million CNY for each project ● 2020, 300CNY/m^2, no more than 10 million CNY for each project
Henan province, Jiaozuo	2018.12	1. Subsidies ● 1000CNY/m^2, no more than 20 million CNY for each project

[a] 1 USD = 6.8 CNY.

guideline and national standard will guide and support the promotion of ZEBs in China at the national level.

2.2.3. Goals and policies (2017–2018)

Along with abundant demonstration projects, Shandong, Beijing, Hebei, Shijiazhuang and other provinces and cities have successively formulated incentive policies to promote the development of ultra-low energy buildings (Table 1). In February 2017, the *Outline of China's* 13th *Five-Year Plan for the Development of Building Energy Efficiency and Green Building*, published by MoHURD, presented a target of 10 million m^2 of ultra-low buildings and nearly-ZEBs by 2020. In addition, in April 2018, Chinese authorities approved and published the master plan for the Xiongan New Area, which pledges to promote ultra-low energy buildings and optimise the energy consumption structure.

2.2.4. Three-step plan for the next three decades (2025-2035-2050)

With the successful demonstration projects and strong policy driven, in general, the building energy efficiency plans in the next stage in China should not only be consistent with the three-step plan proposed in the early 1980s, but also correlate with China's 2025-2035-2050 and other medium-to-long term building energy efficiency upgrading goals. It should not only be consistent with the definitions of international organisations and developed countries to lay the foundation for future development, but must also form its own system to lead the development and transformation of the industry in China.

As building energy efficiency further reduces due to the inconsistent progress of building energy efficiency in different climate zones in China, it is difficult to use the same energy efficiency percentages to define different types of buildings in different climate zones. Therefore, ultra-low energy buildings, nearly-ZEBs and ZEBs are defined based on the attainable standards in 2016, which include *Design standard for energy efficiency of public buildings GB50189-2015*, *Design standard for energy efficiency of residential buildings in severe cold and cold zones. JGJ 26–2010*, *Design standard for energy efficiency of residential buildings in hot summer and cold winter zone JGJ134-2016*, and *Design standard for energy efficiency of residential buildings in hot summer and warm winter zone JGJ75-2012*.

(1) Ultra-low energy building – energy reduction of 50% based on attainable standards in 2016
(2) Nearly-ZEB – energy reduction of 60%–75% based on attainable standards in 2016
(3) ZEB – generated energy more than or equal to building energy consumption

Fig. 2 shows the definitions of ultra-low energy building, nearly-ZEB and ZEB in detail. The technical strategies are similar, which is reducing energy demand via passive techniques and high energy efficiency building systems. For nearly-ZEB and ZEB, the renewable energy is used to replace the remaining energy demand in varying degrees.

Compared to the nearly-ZEB, ZEBs additionally consider the concepts of energy storage, smart grid and distributed energy. Importantly, the energy generation in a ZEB is greater than or equal to its energy consumption, the essential of which is consistent with a positive energy building.

3. NEARLY-ZEB best practices in China

To accelerate the process towards achieving nearly-ZEBs in China, practices are important during the initial development stage to demonstrate to people the possibility of building such high-level energy-efficient buildings and implementing technologies. In September 2016, the China Passive Building Alliance invited approximately 40 members to draw up the casebook *Best Practices of Ultra-Low/Nearly-ZEB in China* (CPBA, 2017) under the direction of MoHURD ('casebook' for short). Templates were used to collect detailed information on selected nearly-ZEBs, such as descriptive information, building envelope components and energy data. This section summarises and evaluates the energy-efficient measures of the practices listed in the casebook. The key technologies and its issues are shown in the next section. As China has not fully developed its own national standard at that time, the practices presented here can mostly fulfil or surpass the envisaged nearly-ZEB requirements.

3.1. General information

Fig. 3 shows the steady increase in the number of nearly-ZEBs in China over the last 7 years. The construction phase of 32 of the 37 buildings has been completed. The other five buildings will be completed in 2018. Please note that the casebook only contains the best practices built and planned by the end of 2016. Since many incentive policies published in 2017 and 2018 (Table 1), aboundant demonstration projects, including serveral communities with more than 200,000 m^2, were developed since then. Until the end of 2018, there is approximately 4 to 5 million square meters best practices in China. Undoubtedly, the growth rate of nearly-ZEBs will increase in the following

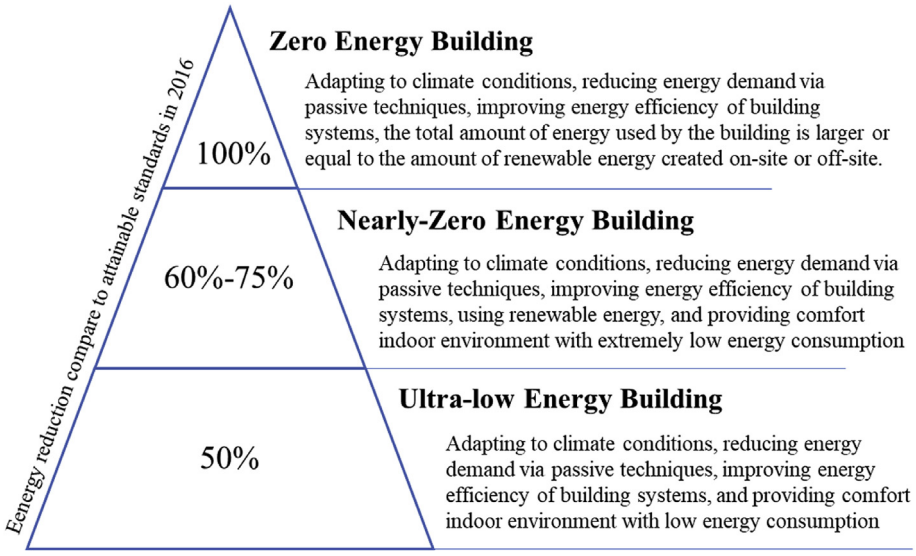

Energy reduction compare to attainable standards in 2016
100%
60%-75%
50%
Zero Energy Building
Adapting to climate conditions, reducing energy demand via passive techniques, improving energy efficiency of building systems, the total amount of energy used by the building is larger or equal to the amount of renewable energy created on-site or off-site.
Nearly-Zero Energy Building
Adapting to climate conditions, reducing energy demand via passive techniques, improving energy efficiency of building systems, using renewable energy, and providing comfort indoor environment with extremely low energy consumption
Ultra-low Energy Building
Adapting to climate conditions, reducing energy demand via passive techniques, improving energy efficiency of building systems, and providing comfort indoor environment with low energy consumption

Fig. 2. Definitions of ultra-low energy building, nearly-ZEB and ZEB in China.

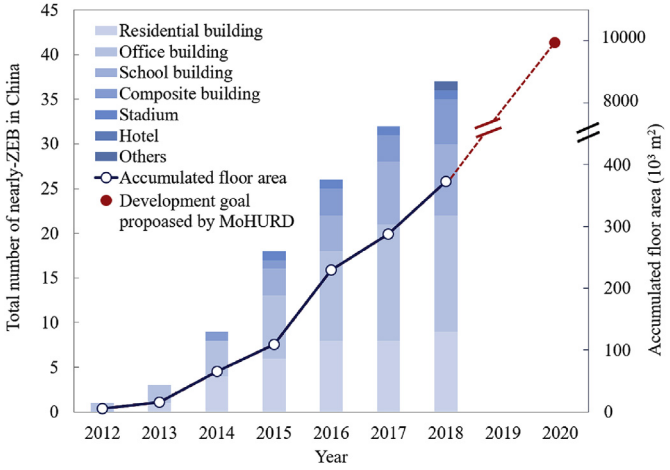


Fig. 3. Growth of nearly-ZEB built and planned by the end of 2016 in China.

few years, as well as the demand for high-performance products and services.

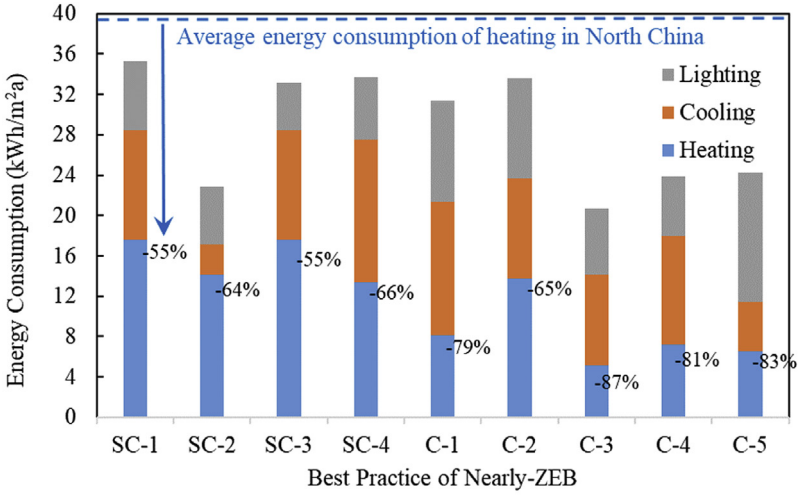
China has great climate diversity. The practices of the nearly-ZEBs presented here cover four climate zones: severe cold (11%), cold (73%), hot summer & cold winter (9%) and hot summer & warm winter (7%). The practices also consist of different types of buildings, in which office buildings, residential buildings and school buildings account for 35%, 24% and 22%, respectively. Building size ranges from 1188 m^2 to 80,955 m^2, with an average of 9921 m^2.

3.2. Energy consumption

Nearly-ZEBs aim to produce as much renewable energy as possible to reduce the reliance on fossil fuels. As not all of the practices provide energy consumption and renewable energy generation data, Fig. 4 shows the calculated energy consumption after cutting down the generated renewable energy during the design stage in the severe cold and cold regions. Fig. 3 indicates that the energy consumption of heating, cooling and lighting range from 20.7 kWh/m^2a to 35.3 kWh/m^2a, with an average of 28.7 kWh/m^2a. According to THUBERC (2017), the energy consumption only for heating in the north was 39 kWh/m^2a in 2016. The results show that best practices are on average 70% more energy efficient than existing buildings.

As most of the practices are newly built, and it is impossible to obtain full access to all of the monitoring data, this study shows 3-years of monitoring data for a specific building C-4. The demonstration building C-4, located in cold climate zone, is a four-storey office building with a floor area of 4025 m^2. The annual energy consumption target, including heating, cooling and lighting, is 25 kWh/m^2. Fig. 5 shows the energy saving potentials for different techniques between the best practice C-4 and a typical building. High-performance building envelops, heat recovery ventilation system, LED lighting and renewable energy can save the energy demand by 33.2%, 16.1%, 17.5% and 39.4%, respectively. In total, 70.8% energy consumption can be saved.

Intelligent building management systems play an important roles to achieve ZEB (Shaikh et al., 2014). It has the ability to monitor and control building systems to improve the performance. In 2014, the energy consumption of heating, cooling and lighting is 27.6 kWh/m^2, which is 10.7% higher than the design target (Fig. 6). Xu et al. (2017) pointed out that this is because the management system was under commissioning. After half year of operation, the measurement results show that the energy consumption meets the design targets. The average energy consumption of heating, cooling and lighting from 2015 to 2017 was 23.4 kWh/m^2, 7% lower than the design target. On average, the HVAC system, lighting and plug load accounts for 48%,



Building[a]	Type	Building Area (m^2)
SC-1	Residential	7,775
SC-2	Public	7,791
SC-3	Public	1,200
SC-4	Public	1,187
C-1	Residential	28,050
C-2	Residential	8,016
C-3	Residential	4,645
C-4	Public	4,025
C-5	Public	14,527

[a] SC and C represent climate region of severe cold and cold, respectively.

Fig. 4. Designed annually energy consumption intensity of the practices of nearly-ZEB and its comparison with the average energy consumption of heating in Northern China in 2016.

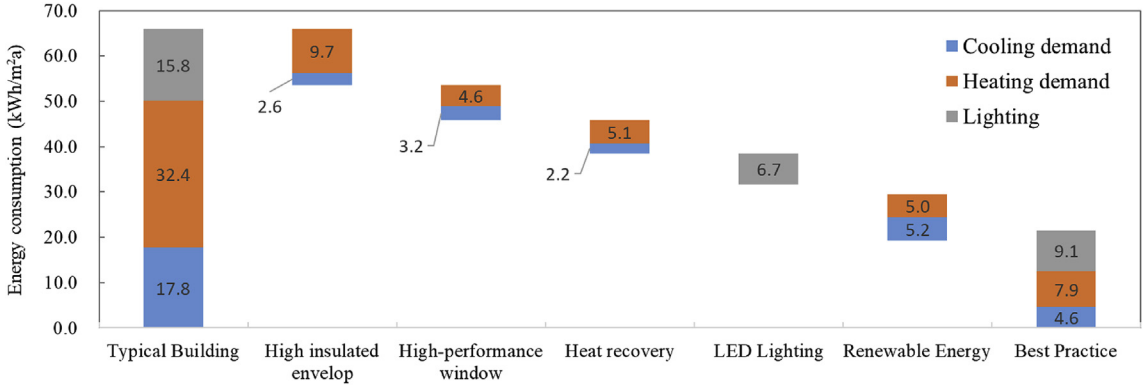


Fig. 5. Energy saving potential for different techniques between the best practice C-4 and a typical building. This figure is modified after Zhang (2016).

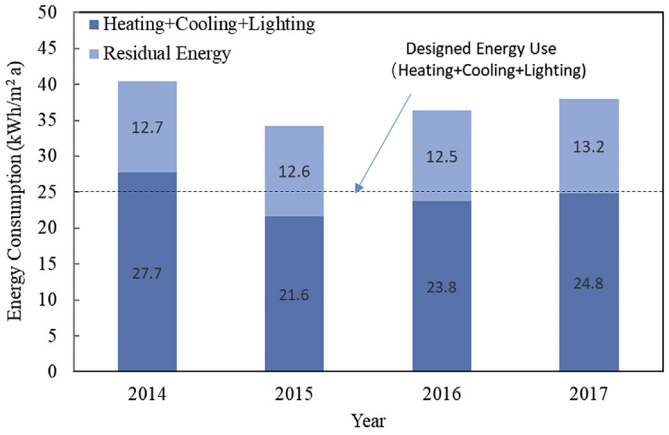


Fig. 6. Monitoring results of energy consumption of the best practice C-4.

17% and 29% of the total energy consumption, respectively.

3.3. Economic analysis

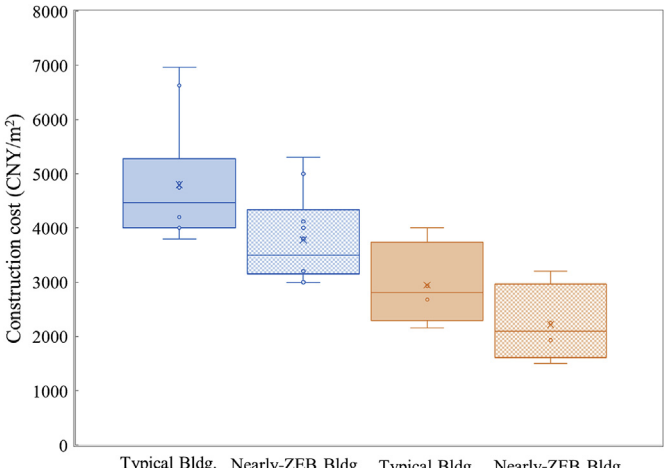
Among all the 37 best practices, 14 of them have open availability of construction cost, in which 10 of them are public buildings and 4 of them are residential buildings. Fig. 7 compares the construction cost between the practices and the typical buildings with the same building characteristics (such as architectural features, finishing et al.) but built under the current energy efficiency standards. It should be noted that these data are the design cost data, not the as-built cost data. The results show that construction cost for nearly-ZEB varies significantly, ranging from 2160 CNY/m^2 to 6960 CNY/m^2. Compare to the typical buildings, nearly-ZEB of public buildings have extra construction cost between 700 CNY/m^2 to 1650 CNY/m^2, with an average of 1014 CNY/m^2. For the residential buildings, the average extra cost is 722 CNY/m^2.

Among all the nearly-ZEB with open availability of construction cost, 11 of them provided breakdown cost (Table 2), which helps to identify how the extra cost arises. In China, the majority of extra cost is because of passive strategy. The cost of materials (like additional insulation and high-performance window system) as well as the additional work (like making the envelop thermal bridge free and air tight) make passive strategy is the most important aspect. The impact of renewable energy and active strategy is quite low. China's renewable energy has grown fast driven by the “Renewable Energy Law” and other relevant policies since 2005. The consequences are that the installation cost of renewable energy is quite low in China. Certainly, the impact also depends on the installed capacity, and Table 2 shows that there are large variations.

4. Key technical strategies in ZEB development in China

China has significant cultural and climatic diversity in different regions. Therefore, buildings in China have unique characteristics. First, the indoor environment quality is lower than that of Western countries (Hu, 2013; Wang et al., 2004). Furthermore, the fresh air of residential buildings is always supplied by opening windows instead of mechanical ventilation systems. Second, as mentioned above, the climate in China is extremely diverse. From the heating and cooling degree days perspectives, the average annual cooling degree days for Shenzhen, Wuhan and Beijing are 2,107, 1189 and 840, respectively (Sivak, 2009). Third, unlike Western countries, most of the residential buildings in large cities in China are high-rise buildings. Fourth, although public buildings in China provide less thermal comfort than the buildings in the US, they use much less energy than the buildings located in equivalent weather conditions in the US (Hu, 2013; Xu et al., 2013).

In this session, key technical strategies and its issues of ZEB development in China are analysed, on the basis of the information collected from the best practices. However, the information is not fully available for all of the demonstration buildings. After thorough analysis, 14 buildings are appraised for their reasonable and complete information. The usage ratio of different technical strategies in best practices can be seen in Fig. 8.



	Public Bldg.	Residential Bldg.
Extra cost (CNY/m²)	1014	722

Fig. 7. A comparison of the construction cost between the nearly-ZEB and the same typical building built following the current energy efficiency standards.

Table 2
Cost breakdown of the best practices.

Building[a]	Passive strategy	Active strategy	Renewable energy	Advanced control
C-1	55%	8%	32%	5%
C-2	80%	0%	5%	15%
C-3	79%	3%	18%	0%
C-4	50%	10%	10%	30%
C-5	70%	25%	2%	3%
C-6	79%	21%	0%	0%
C-7	92%	8%	0%	0%
C-8	35%	10%	43%	12%
C-9	30%	60%	10%	0%
SC-1	76%	10%	5%	9%
SC-2	35%	25%	30%	10%
Average	62%	16%	14%	8%

[a] C, SC represent cold and severe cold climate zones, respectively.

4.1. Passive techniques

Extremely low *U*-values of the envelope represent the key technique for ZEBs (Feist et al., 2005). Many studies have shown the negative relationship between the *U*-value and energy-saving potential (Aste et al., 2009; Yang et al., 2012; Yu et al., 2008). Zhang (2016) illustrated that the high-performance of building envelop only may reduce the heating demand by 75% and 50% for sever cold and cold climate zones in China, respectively. For the demonstration projects in China, insulation materials, such as mineral wool, expanded polystyrene and extruded polystyrene, are widely used. One of the practices uses state-of-the-art thermal insulation material and a vacuum insulation panel. On average, the *U*-value of the roof and wall for the high-performance building is 68% and 70% lower than that of building energy efficiency standards, respectively (Table 3). For regions in which cooling dominates the energy consumption, Wang et al. (2014) illustrated that high-performance envelopes may increase the annual energy consumption. Heat gains cannot be easily released from well-insulated envelopes in summer. Also, high-performance envelopes in such areas have little effect on reducing the heating load in winter due to dehumidification (Boyano et al., 2013; Zhou and Zhao, 2013). Therefore, the difference of the *U*-values between the best practices and the building energy efficiency standards in hot summer & cold winter climate zone is smaller than that in severe cold and cold climate zones (Table 3). Understanding the dynamic heat balance process, which is related to the heat gain from indoors and solar radiation, insulation performance and ventilation rate, is crucial in cooling-dominated climates.

A high-performance window is an important component. To minimise the amount of heat gain and loss, double or triple glazing systems with low-e glass and inert gas filled in the cavity are used (Li et al., 2013). The *U*-value of the whole window is a function of the *U*-value of the glazing and frame. It is also influenced by the size of the window and the linear heat transfer coefficient for the edge seal of the glazing. For the demonstration buildings in China, eight buildings are equipped with triple-pane windows and six are coated with low-e film. Two buildings have double-glazing. Detailed descriptions of the window system are not available for the remaining four buildings. On average, the *U*-value of the window system for the high-performance building is 0.84 W/m^2K, which is 62% lower than that of building energy efficiency standards. Grynning et al. (2013) pointed out that the *U*-value of state-of-the-art windows available on the market can reach 0.4 W/m^2K. This is equal to or even better performing than insulated opaque walls. The performance of windows used in best practices is much higher than current building energy efficiency standards in China, and there is a need to further develop high-performance components.

Exterior shading devices are widely used in ZEBs, as they can effectively block solar radiation and further reduce the cooling load in summer (Capeluto, 2003; Palmero-Marrero and Oliveira, 2010). As mentioned above, high-rise buildings are popular in China. If it is assumed that the vertical distribution of horizontal mean wind speed can be described as the log wind profile (Stull, 1988), the wind at the height of 60 m is approximately 1.8 times larger than that at the height of 10 m. Therefore, the ability to resist strong wind forces must be considered.

4.2. High energy-efficiency products and renewable energy systems

All of the practices use a mechanical ventilation system equipped with heat recovery. The designed sensible heat exchange efficiency of the heat recovery ranges from 72% to 79%. Heat recovery ventilation systems are more energy consuming than systems without heat recovery, as heat recovery systems require more powerful fans to overcome the air resistance of the heat exchanger. From the annual energy consumption point of view, the heat recovery systems in China are more effective in climates with extreme winters, such as those of Beijing and Harbin. In mild climates, such as those of Guangzhou and Chengdu, the energy consumed by the fans may exceed the energy saving potentials from the heat recovery systems (THUBERC, 2017). The adaptability of heat recovery ventilation systems for different climate zones must be carefully evaluated at the design stage.

The building services systems of nearly-ZEBs, instead of relying on one energy source system, always integrate a mix of different energy

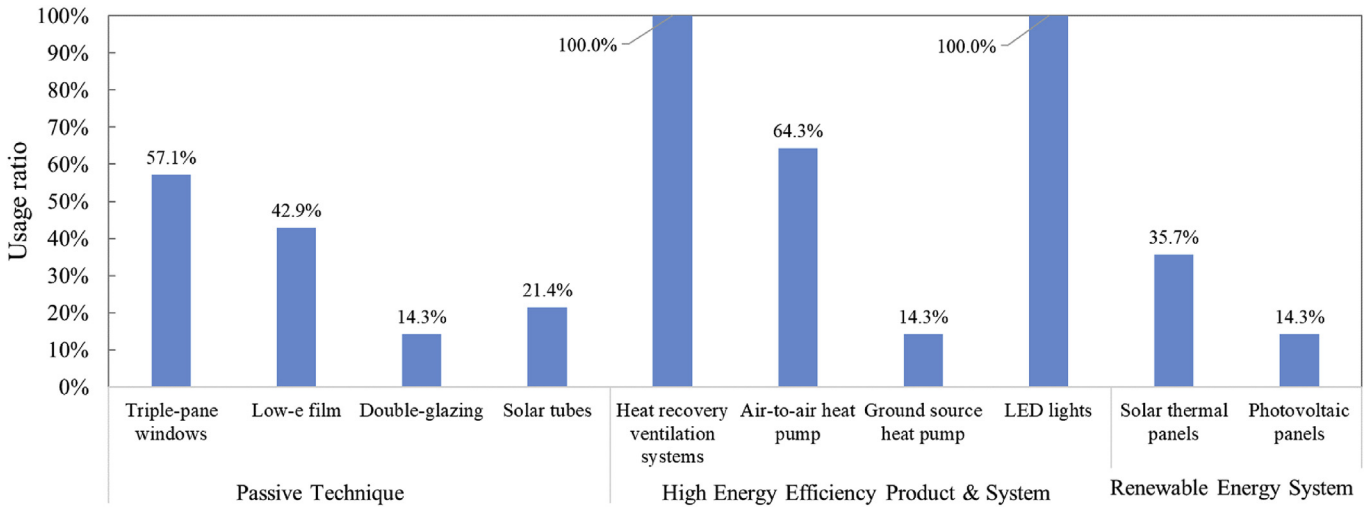


Fig. 8. Usage ratio of different technical strategies in best practices.

Table 3
A Comparison of *U*-values for building components between the practices and the building energy efficiency standards.

Building [a]	Roof			Wall			Window system		
	U-value W/m^{2}K	StandardW/m^{2}K	Difference	U-value W/m^{2}K	StandardW/m^{2}K	Difference	U-value W/m^{2}K	StandardW/m^{2}K	Difference
C-1	0.14	0.45	69%	0.20	0.50	60%	1.1	2.4	54%
C-2	0.12	0.45	73%	0.17	0.50	66%	0.8	2.4	67%
C-3	0.14	0.45	69%	0.14	0.70	80%	1.0	2.5	60%
C-4	0.14	0.45	69%	0.13	0.50	74%	0.8	2.4	67%
C-5	0.11	0.45	77%	0.13	0.70	82%	1.0	2.5	60%
C-6	0.14	0.45	69%	0.13	0.50	74%	1.0	2.4	58%
C-7	0.11	0.35	69%	0.14	0.45	69%	0.8	2.0	60%
C-8	0.12	0.35	66%	0.14	0.45	69%	0.8	2.0	60%
C-9	0.11	0.45	76%	0.12	0.50	76%	0.9	2.4	63%
C-10	0.13	0.45	71%	0.13	0.50	74%	0.8	2.4	67%
SC-1	0.11	0.35	69%	0.15	0.43	65%	0.8	2.3	65%
SC-2	0.11	0.35	69%	0.12	0.43	72%	0.9	2.3	61%
SC-3	0.10	0.25	60%	0.10	0.50	80%	0.8	2.0	60%
HSCW-1	0.2	0.4	50%	0.27	0.6	55%	1.0	2.6	62%
Average	0.13	0.40	68%	0.15	0.52	70%	0.84	2.33	62%

[a] C, SC, HSCW represent climate region of cold, severe cold and hot summer & cold winter, respectively.

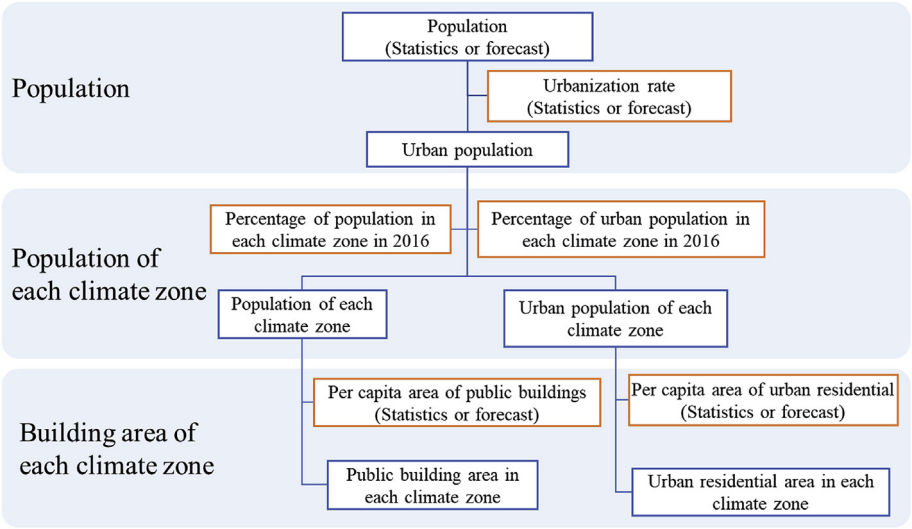

Population
Population (Statistics or forecast)
Urbanization rate (Statistics or forecast)
Urban population
Population of each climate zone
Percentage of population in each climate zone in 2016
Percentage of urban population in each climate zone in 2016
Population of each climate zone
Urban population of each climate zone
Building area of each climate zone
Per capita area of public buildings (Statistics or forecast)
Per capita area of urban residential (Statistics or forecast)
Public building area in each climate zone
Urban residential area in each climate zone

Fig. 9. Calculation scheme to derive building area of each climate zone.

Table 4
Building area development for different climate zones.

	Building[a]	2015	2020	2025	2030	2035	2040	2045	2050
Urban residential building area (10^2 million m^2)	Severe cold	28	33	36	40	42	44	46	48
	Cold	64	77	85	92	98	103	108	112
	HSCW	82	98	109	118	126	132	139	144
	HSWW	36	43	47	51	55	58	60	63
	Temperate	11	13	15	16	17	18	19	19
Public building area (10^2 million m^2)	Severe cold	14	17	20	22	24	27	29	30
	Cold	35	42	49	55	60	65	70	75
	HSCW	43	52	60	67	74	80	86	92
	HSWW	17	21	24	27	30	32	35	37
	Temperate	7	8	10	11	12	13	14	15

[a] HSCW and HSWW represent hot summer & cold winter and hot summer & warm winter climate zones, respectively.

sources (at least one of which is renewable) to feed the energy converters (Fabrizio et al., 2014). Renewable energy is used not only for the electric generation, but also for heating or cooling, domestic hot water production and mechanical ventilation to replace the fossil fuels. Two out of 14 of the best practice use a ground source heat pump, which is the optimum choice in regions where the heating and cooling demands are balanced. Nine out of 14 buildings use an air-to-air heat pump. Solar thermal panels are integrated in 5 out of 14 practices to supply domestic hot water, whereas only 2 out of 14 buildings adopt photovoltaic panels for electricity generation. The technology of solar cooling and heating, although it has not been widely used due to low energy density, instability and poor economy, is applied in two buildings. The low energy demand of nearly-ZEBs reduces the installation scale, thereby improving its economy.

Due to the spatial and temporal variability of renewable energy, it is important to coordinate the relationships between the renewable

Table 5
Existing building energy intensity of heating, cooling and lighting and its development towards 2050 for different climate zones.

	Building[a]	2015	2020	2025	2030	2035	2040	2045	2050
Residential Building (kgce/m^2)	Severe cold	10.7	11.1	11.1	11.5	11.9	12.3	12.6	13.0
	Cold	10.7	11.1	11.1	11.5	11.9	12.3	12.6	13.0
	HSCW	4.7	5.5	6.2	6.8	7.5	8.2	8.8	9.5
	HSWW	4.7	5.5	6.2	6.8	7.5	8.2	8.8	9.5
	Temperate	4.7	5.5	6.2	6.8	7.5	8.2	8.8	9.5
Public Building (kgce/m^2)	Severe cold	22.2	22.2	22.1	22.0	21.9	21.8	21.6	21.5
	Cold	22.2	22.2	22.1	22.0	21.9	21.8	21.6	21.5
	HSCW	13.5	14.6	15.5	16.5	17.4	18.3	19.3	20.2
	HSWW	13.5	14.6	15.5	16.5	17.4	18.3	19.3	20.2
	Temperate	13.5	14.6	15.5	16.5	17.4	18.3	19.3	20.2

[a] HSCW and HSWW represent hot summer & cold winter and hot summer & warm winter climate zones, respectively.

Table 6
Energy consumption intensity for ultra-low energy building and nearly-ZEB.

	Ultra-low energy building	Nearly-ZEB	ZEB
Public Bldg. (kgce/m^2)	13.3	10.7	0
Residential Bldg. (kgce/m^2)	7.6	6.1	0

energy systems (i.e., the building-integrated photovoltaic heat pump), energy storage systems, appliances and grid to improve the efficiency and utilisation rate of renewable energy. Also, due to the building features in China, renewable energy systems may lead to serious obstacles. For example, for the centralised domestic hot water system, previous studies have shown that a large amount of the total energy collected from the solar collector is dissipated through the distribution and circulation pipe (Feng et al., 2017; THUBERC, 2017) due to the lower hot water consumption per capita than in developed countries and the large vacancy rate of the buildings. Johnston (2007) also demonstrated the advantages of installing solar panels on each floor, instead of only on the top of the building, to solve the high-energy demand density problems for high-rise buildings in China (Fong and Lee, 2012). However, the area of the solar collectors for each floor should be carefully designed to avoid uneven distribution of solar radiation along the building's height (Shi et al., 2013; Yang et al., 2017).

4.3. Design, construction and testing

Designing nearly-ZEBs is a complex task that integrates various design strategies. The energy demand is usually used as the evaluation criteria. Therefore, a simplified method for checking the performance compliance within the context of building regulations is required. The quasi-steady energy calculation method proposed by EN ISO 13790 has been widely used. The energy balance is calculated on a monthly basis and the dynamic effects are considered by introducing utilisation factors. The features of simplified input and simplified method combined with transparency, reproducibility and robustness with adequate accuracy make this method suitable for compliance checking (van Dijk et al., 2005). Many compliance checking tools are based on this method, such as the Passive House Planning Package tool developed by the Passive House Institute. The China Academy of Building Research also developed an energy simulation tool called the IBE based on the quasi-steady method (Yu et al., 2018). The method is fit for the energy simulation of Chinese residential buildings in cold areas, but its adaptability to other climate regions must be studied further.

Thermal bridging occurs where the thermal conductivity of the materials is much higher than the building envelopes. Heat loss due to thermal bridging may account for 11%–29% of the energy demand for heating (Evola et al., 2011). The proportion is be higher for high-performance buildings (Zhu and Lin, 2004). A cost-benefit analysis should be conducted to determine the balance between the additional cost of construction and the energy savings produced by thermal bridge correction (Evola et al., 2011). Thermal bridges are characterised by multi-dimensional heat transfer and detailed calculation is complex and time consuming. Many European countries (e.g., Denmark, France, Germany and Spain) have adopted simplified approaches based on thermal bridge atlases, which are much easier and faster (Roels et al., 2011). As envelop insulation has raised much attention in China, it is necessary to develop a detailed thermal bridge atlas, where every building envelope is described with different wall thickness and thermal transmittance and can be easily applied by contractors, architects and engineers.

Nearly-ZEBs require high-quality components. As described above, most of the *U*-values of super-insulated window systems are in the order of magnitude of 10^{-1} W/m^2·K, which leads to the problem that China currently lacks corresponding testing methods and standards for such high-level insulation components. According to the National Standard *Graduation and Test Method for Thermal Insulating Properties of Doors and Windows GB/T 8484-2008*, the hot box method is applied for thermal insulation testing and has been widely used for different standards throughout the world (Asdrubali et al., 2012). However, the testing facility only has an accuracy of ± 0.1 W/m^2·K, which is obviously inappropriate for high-quality component testing.

5. Energy saving potential through ZEB development

In this section, six scenarios are presented to study the peak building energy consumption and energy saving potentials by considering the impact of ZEBs in China towards 2050.

5.1. Methodologies

5.1.1. Building energy consumption

Building energy consumption is related to energy intensity and building area. Thus, both temporal variations of intensity and building area must be studied. Also, there are differences in energy use between residential buildings and public buildings and between different climate zones. Therefore, energy intensity must be treated differently.

In this study, buildings are divided into two types, residential buildings and public buildings. They are denoted by *k*. They are also divided into five climate zones: severe cold, cold, hot summer cold winter, hot summer warm winter and temperate. The climate zones are denoted by *i*. The buildings also consist of existing buildings, ultra-low energy buildings, nearly-ZEBs and ZEBs. The total building energy consumption is measured as primary energy, including conversion and transport or transmission losses, which can be expressed as follows:

$$E_{building} = \sum_i \sum_k e_{existing,i,k} A_{i,k} f_{existing} + e_{ultra-low,i,k} A_{i,k} f_{ultra-low} + e_{NZEB,i,k} A_{i,k} f_{NZEB} + e_{ZEB,i,k} A_{i,k} f_{ZEB} \quad (1)$$

where E is total building energy use; e is the energy intensity; A is the building area; and f is the area percentage of different building types. In

Table 7
Percentage of different building types for study scenarios.

		2015	2020	2025	2030	2035	2040	2045	2050
BAU	Existing Bldg.	100%	100%	90%	80%	70%	50%	30%	10%
	Ultra-low energy Bldg.	0%	0%	10%	20%	30%	40%	50%	60%
	Nearly-ZEB	0%	0%	0%	0%	0%	10%	20%	30%
	ZEB	0%	0%	0%	0%	0%	0%	0%	0%
S1 - Slow	Existing Bldg.	100%	90%	80%	70%	50%	30%	0%	0%
	Ultra-low energy Bldg.	0%	10%	20%	30%	40%	50%	50%	30%
	Nearly-ZEB	0%	0%	0%	0%	10%	20%	40%	50%
	ZEB	0%	0%	0%	0%	0%	0%	10%	20%
S2 - Conservative	Existing Bldg.	100%	90%	80%	50%	20%	0%	0%	0%
	Ultra-low energy Bldg.	0%	10%	20%	40%	60%	60%	40%	0%
	Nearly-ZEB	0%	0%	0%	10%	20%	30%	40%	60%
	ZEB	0%	0%	0%	0%	0%	10%	20%	40%
S3 - Moderate	Existing Bldg.	100%	90%	70%	50%	0%	0%	0%	0%
	Ultra-low energy Bldg.	0%	10%	20%	30%	60%	40%	0%	0%
	Nearly-ZEB	0%	0%	10%	20%	30%	40%	60%	40%
	ZEB	0%	0%	0%	0%	10%	20%	40%	60%
S4 - Aggressive	Existing Bldg.	100%	80%	60%	30%	0%	0%	0%	0%
	Ultra-low energy Bldg.	0%	10%	20%	30%	40%	0%	0%	0%
	Nearly-ZEB	0%	10%	20%	30%	40%	70%	40%	20%
	ZEB	0%	0%	0%	10%	20%	30%	60%	80%
S5 - Leapfrog	Existing Bldg.	100%	90%	60%	30%	0%	0%	0%	0%
	Ultra-low energy Bldg.	0%	5%	20%	30%	20%	0%	0%	0%
	Nearly-ZEB	0%	5%	10%	20%	50%	60%	20%	0%
	ZEB	0%	0%	10%	20%	30%	40%	80%	100%

this study, only residential buildings in urban areas and public buildings are considered. Residential buildings in rural areas are excluded. Furthermore, the calculation boundaries only include energy use for heating, cooling and lighting.

5.1.2. Building area for different climate zones

Building area is a function of population, urbanisation rate and per capita area (Fig. 9). The Communiqué of the Fifth Plenary Session of the 18th CPC Central Committee announced a new policy allowing Chinese couples to have two children to help address the ageing issue in China. Zhai et al. (2016) analysed the impact of the new policy on the population in China. They showed that the population will peak around 2030 at approximately 1.45 billion people, which is consistent with the *National Population Development Plan (2016–2030)* issued by State

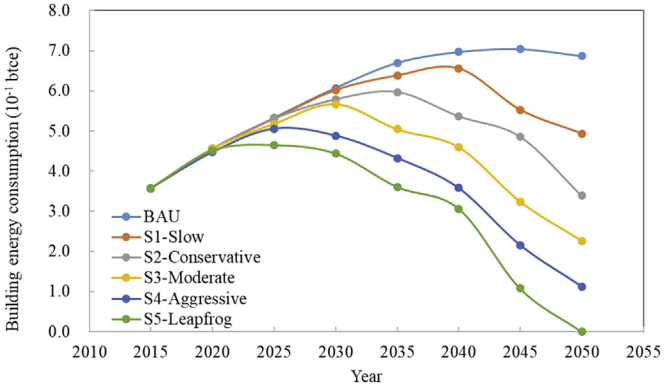


Fig. 10. Building energy consumption pathway 2015–2050 for six scenarios.

Table 8
Building energy consumption peak and its occurrence time.

	Peak (million tce)	Peak Year
BAU	704	2045
S1-Slow	656	2040
S2-Conservative	596	2035
S3-Moderate	567	2030
S4-Aggressive	506	2025
S5-Leapfrog	465	2025

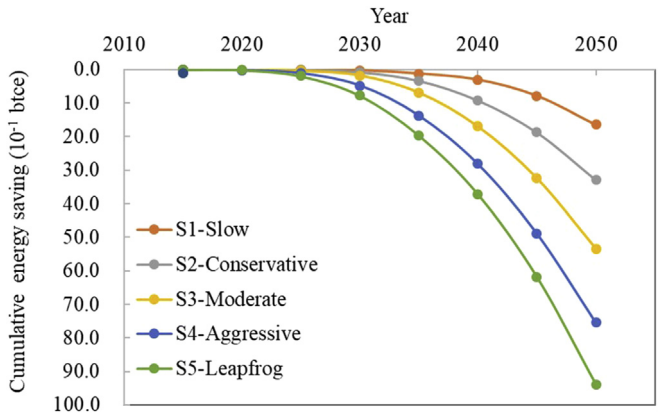


Fig. 11. Cumulative building energy saving from 2015 to 2050 for six scenarios.

Council. Therefore, the 2050 population forecasted by Zhai et al. (2016) is used here. The urbanisation rate, and further, the population in urban and rural areas can be obtained from existing reports (CERI, 2014). According to the China Statistical Yearbook 2016 (NBS, 2016), the (urban) population percentage of each climate zone can be derived. It is assumed that this percentage will remain constant in the future.

THUBERC (2017) indicated that the average residential area per person in Western countries ranges from 40 m^2/person to 70 m^2/person. The report of the Standards and Norms Institute of MoHURD indicated that the number will reach 33 m^2/person in China (SNI, 2017). It assumes that under strictly controlled situations, the urban residential area per capita will reach 35 m^2/person in 2050. After analysing the current status and development trend of public buildings in China, Peng and Jiang (2015) pointed out that the per capita public building area should be controlled within 18 m^2/person. Thus, in this study, the per capita public building area is 18 m^2/person in 2050. By assuming the building area per capita maintains linear growth from 2015, the development trend of the building area of residential buildings in urban areas and public buildings in different climate zones can be derived (Table 4).

5.1.3. Building energy consumption intensity

Many studies have calculated and predicted building energy intensity (Jiang et al., 2014; Li, 2008). One report simulated the energy intensity of different types of buildings for nine typical cities (SNI, 2017). However, as only typical buildings for typical cities were simulated, some results were relatively low. Yang (2009) established a model for analysing the energy consumption of buildings in China. The model distinguishes the difference between urban and rural residential buildings and considers the impact of people's lifestyle on energy consumption. Based on this model, Peng and Jiang (2015) established a building energy analysis model considering technical and behavioural factors. Yang (2009) also applied this model to predict building energy consumption intensity towards 2030. The results showed linear growth under each scenario. This study expects the energy consumption intensity for existing buildings to maintain its growth trend based on historical data derived from THUBERC (2017). Studies have shown that the energy intensity proportion of heating, cooling and lighting for residential buildings is 46.6% (THUBERC, 2017). This study also assumes that the proportion is 60% for public buildings. The energy intensity of heating, cooling and lighting is thereby derived in Table 5.

For the energy consumption of ultra-low energy buildings and nearly-ZEBs, the average energy consumption intensity after removing the generated renewable energy derived from the casebook is used here (Table 6). The intensity only consists of heating, cooling and lighting. For ZEBs, where the total amount of energy used by the building is roughly equal to the amount of renewable energy created, the energy consumption intensity is 0.

For the residential buildings, both the heating and cooling demand varies a lot for different climate zones. However, in total, the building energy consumption intensity for ultra-low energy building and nearly-ZEB is similar for different climate zones. Also, for public buildings, the energy consumption intensity is determined by the type of public building, e.g. hotels, office buildings, hospitals et al., rather than the climate zones. Therefore, it is assumed that the energy consumption intensity of ultra-low energy building and nearly-ZEB for different climate zones is the same.

5.2. Scenario analysis

5.2.1. Scenario description

To explore the possible pathway and policy options for building energy efficiency and emission reduction in China, six scenarios are set up on the basis of China's current economic and social development status. In the BAU scenario, China will begin to develop ultra-low energy buildings and nearly-ZEBs in 2020 and 2035, respectively. In 2050, the percentage of existing buildings, ultra-low energy buildings and nearly-ZEBs is 10%, 60% and 30%, respectively. From the BAU to the leapfrog development scenario, building energy efficiency development gradually enhances. The starting time of the development of ultra-low energy building, nearly-ZEB and ZEB is in advance. In the leapfrog development case, the development of ZEBs will begin in 2020. Furthermore, all of the buildings in China will be ZEBs by 2050. The percentage of existing building equals to 0% means all the buildings in 2015 are retrofitted or rebuilt to ultra-low energy buildings, nearly-ZEB, and ZEB. The table below provides detailed definitions of the scenarios (Table 7).

5.2.2. Results

Fig. 10 presents six possible building energy pathways towards 2050. Different building development strategies deliver very different futures. In 2015, the building energy consumption was 358 million tce, which only consists of the energy consumption of heating, cooling and lighting for urban residential buildings and public buildings. The energy consumption for the appliances and buildings in rural areas are excluded. For all of the scenarios, building energy consumption first increases and then decreases. The enhancement of building energy

efficiency development, from the BAU scenario to the leapfrog development scenario, shows the following:

1) The peak decreases.
2) The occurrence time of the peak advances.
3) The decline rate after the peak increases.

In the BAU scenario, the peak will reach 704 million tce in 2045 and then building energy consumption will be slightly reduced. In 2050, building energy consumption for BAU will be 687 million tce. In the leapfrog development scenario, in which ZEBs will begin to develop in 2020 and all buildings in China will be ZEBs by 2050, the peak will occur in 2025 and the energy consumption will be 0 by 2050. Table 8 shows the building energy consumption peak and its occurrence time. It indicates that most of the peak occurs when the percentage of the existing buildings decreases to approximately 50%. In general, only if the total percentage of ultra-low energy buildings, nearly-ZEBs and ZEBs is larger than 50% does the building energy consumption begin to drop. Furthermore, from the slow development scenario to the leapfrog development scenario, the energy consumption in 2050 is expected to be smaller than that in 2015.

Fig. 11 presents the cumulative energy saving compared to the BAU scenario. It clearly shows that with the acceleration of building energy efficiency development, the cumulative building energy saving increases dramatically. From 2015 to 2050, scenarios 1, 3 and 5 substantially reduce the energy consumption by 1,642, 5340 and 9380 million tce, respectively.

5.3. Discussion

From the analysis above, ZEB promotion is a promising way of relieving dependence on fossil fuels in the building sector. At the initial development stages, the government's adornments are necessary. First, technical guidelines and short-term development goals are provided. Although they do not directly create investment, they give investors and householders a signal that governments are promoting ZEBs, which will be built under certain technology strategies and have long-term benefit. Second, incentive policies and subsidies are announced to stimulate the investment. As at 2018, Beijing, Hebei Province and Jiangsu Province had already published related policies. The incentive measures include subsidies, land use support, floor area ratio bonus and reduced city infrastructure supporting fees.

For the medium-to-long term, mandatory regulations are the most powerful tool to promote ZEBs. From the study above, the more aggressive the development pathway, the higher the energy saving potential is. The speed relies on economic and technological development.

6. Conclusions

After 30 years of development, led by building energy efficiency standards, China has accomplished the three-step building energy efficiency plan it proposed in the 1980s. For the next 30 years, from now until 2050, China should set development goals based on said three-step plan and international consensus. This study proposes a definition hierarchy, which includes ultra-low energy buildings, nearly-ZEBs and ZEBs, as the medium-to-long term building energy efficiency upgrading goals in China for the next three decades.

In the past few years, many pilot and demonstrative ultra-low energy buildings and nearly-ZEBs have been built in various regions and climates. The results of the detailed analysis of existing demonstration projects in China show that the energy consumption of heating in North China is 70% lower on average than existing buildings. Compared to the goal proposed by national and local governments during the 13th Five-Year Plan period, nearly-ZEBs have broad prospects in China. Technical strategies and its issues are also thoroughly analysed.

A set of scenarios was developed and analysed to measure medium-to-long term energy saving potentials of ZEBs. With accelerated rate of development, the results show that 1) the peak decreases; 2) the occurrence time of the peak advances; and 3) the decline rate after the peak increases. In general, only if the total percentage of ultra-low energy buildings, nearly-ZEBs and ZEBs is larger than 50% does the building energy consumption begin to decrease. Compared to the BAU scenario, the accumulated saving of fossil fuels can be reduced by up to 9,380 million tce in 2050.

It is no doubt that ZEBs are a feasible and accessible solution to reducing energy consumption in the building sector. In the initial stage, related incentive policies are necessary to guide the participation of social funds and to promote the formation of a market-oriented operation mechanism. In the long term, the speed of development will depend on economic and technological development.

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